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PARENT-FLARE EMISSION AT 2.8 GHZ AS A PREDICTOR OF THE PEAK ABS--ETC(U)
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PARENT-FLARE EMISSION AT 2.8 GHz AS A PREDICTOR OF THE PEAK ABSORPTION OF POLAR-CAP EVENTS

Edward W Cliver, 1st LT USAF OLC, 12 WSq,
3 WWg, AWS (MAC)

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E to the 0.5555 power

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where E is given in sfu-min.

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absorption predicted by this formula is within a factor of 2 of that actually observed for 22 of the 32 principal PCA events (69 percent) and within a factor of 3 for 28 of the 32 (88 percent). A correction for the effect of the interplanetary magnetic field on particle propagation is considered in the appendix.

OBJECTIVE

Develop earth environment-disturbance forecasting techniques to predict degradation effects on military communications, navigation, and surveillance and on weapon systems which use electromagnetic radiation.

RESULTS

Forty-seven Polar Cap Absorption Events which occurred during the nineteenth and twentieth solar cycles were studied. Parent-flare 2.8-GHz event energy was correlated with peak riometer absorption for these events. Thirty-two of the events had riometer absorption $\geqslant 2.0$ dB. The least-squares relationship between the peak absorption (A) and the burst energy (E) is given by

$$A(\mathrm{dB}) = 0.0116\ E\ (\mathrm{Sfu \cdot min})^{0.5555}$$

with a correlation coefficient (R) of 0.59. The peak absorption predicted by this formula is within a factor of 2 of that actually observed for 22 of the 32 principal PCA events (69 percent) and within a factor of 3 for 28 of 32 (88 percent) events.

ADMINISTRATIVE INFORMATION

This work was performed by members of the Propagation Division, Electromagnetic Systems Department, of the Naval Electronics Laboratory Center between May 1975 and July 1976 under Program Element 62759N, Project F52551, and Task Area WF52551717 (NELC M207). This report was approved for publication 1 December 1976.

The author is grateful to DF Smart, MA Shea, and RM Straka for helpful discussions and also thanks AE Covington for kindly providing unpublished radio data from the nineteenth solar cycle.

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INTRODUCTION

Polar Cap Absorption (PCA) events caused by low-energy ($\approx$ 10 MeV) protons ejected from intense solar flares can disrupt high-frequency communications in the earth's polar regions for periods of days. The spatial and temporal extent of the PCA event make it of particular concern to the US Air Force. The time delay between the optical and radio observation of the flare and the arrival of flare particles enables the solar forecaster at the Air Force Global Weather Central (AFGWC) to notify customers, who use the polar-region ionosphere in their communications networks, of the impending occurrence and expected intensity of a PCA.

The spectral shape of the Type IV microwave radio emission associated with large flares has proven a useful tool for predicting whether or not a given flare will produce a principal ($\geqslant$ 2.0 dB) riometer absorption event (ref 1–3). Several methods (ref 4–12) have been developed to forecast the intensity of a solar particle event based upon other parameters of the parent-flare microwave burst. These methods are reviewed in table 1.

The first four studies attempted correlations between burst parameters and time-integrated proton fluxes. Straka and Barron (ref 8) were the first to consider correlations with peak proton fluxes and riometer absorption. In a follow-up study based upon data from the range of discrete frequencies monitored at Sagamore Hill Observatory, Straka concluded that the integrated burst flux density (event energy) at the longer centimetre and decimetre wavelengths was a useful predictor of the size of PCA events (ref 9). Croom obtained a high correlation (0.8) between parent-flare burst mean duration and peak 10-MeV proton flux for a relatively large data sample, but this method has yet to receive an operational test (ref 10). An analysis by this author of 32 solar particle events, detected by the Goddard Space Flight Center Experiment aboard Explorers 34 and 41, revealed a correlation coefficient of only $\approx$ 0.5 between the 2.8-GHz event mean duration and the peak 6–19-MeV proton flux. The methods developed by Newell (ref 11) and Castelli et al (ref 12) are currently in use at AFGWC.

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9. AFCRL Space Forecasting Research Note 2, The Use of Solar Radio Bursts as Predictors of Proton Event Magnitude, by RM Straka, 1970
10. Croom, DL, "Forecasting the Intensity of Solar Proton Events from the Time Characteristics of Solar Microwave Bursts," Solar Physics, v 19, p 171, 1971
11. AFCRL Technical Report 72-0543, Forecasting Peak Proton Flux and PCA Event Magnitudes Using 'Flash-Phase' Integrated Radio-Burst Flux Density, by DT Newell, 1972
12. AFCRL Technical Report 73-0086, Solar Radio Activity in August 1972, by JP Castelli, WR Barron, and J Aarons, 1973

TABLE 1. REVIEW OF METHODS FOR PREDICTING THE INTENSITY OF SOLAR PARTICLE EVENTS BASED UPON MICROWAVE BURST DATA.

Investigator	Frequency	Predictor (Burst Parameter)	Predictand	Number of Events
Webber (1963)[4]	10 GHz	Energy	Time-integrated intensity of >10-MeV particles.	13
Fletcher (1964)[5]	2.8 GHz	Duration, peak flux density, rise rate, ratio of the duration of the burst to the duration of the burst at one-half peak flux density.	Time-integrated flux of >30 MeV protons.	23
Lopez et al (1966)[6]	2.8 GHz 3.75 GHz	Energy, energy above a 50-Sfu baseline, energy above baselines of 10 and 20 percent of the burst's peak flux density, peak flux density, duration, mean flux density.	Time-integrated flux of >30 MeV protons.	20
Gonzalez and Divita (1968)[7]	2.8 GHz	Energy, peak flux density, product of burst duration and peak flux density.	Time-integrated flux of >30-MeV protons.	24
Straka and Barron (1969)[8]	500 MHz to 8.5 GHz	Total integrated radio-flux density from 500 MHz to 8.5 GHz.	Peak proton flux >10 MeV. Peak riometer absorption at 30 MHz.	16
Straka (1970)[9]	606 MHz, 1.4, 2.7, 5.0, 8.8, and 15.4 GHz	Energy, mean flux density, peak flux density, duration.	Peak proton flux >10 MeV. Peak riometer absorption at 30 MHz.	15
Croom (1971)[10]	5 to 20 GHz	Mean duration.*	Peak proton flux >10 MeV, >30 MeV, >60 MeV.	27
Newell (1972)[11]	606 MHz, 1.4, 2.7, 5.0, 8.8 GHz	Semi-integrated flux density.	Peak proton flux >10 MeV. Peak riometer absorption at 30 MHz.	16
Castelli et al (1973)[12]	8.8 GHz	Energy	Peak proton flux >10 MeV.	21

*Croom[10] considered several single-frequency and multifrequency parameters of microwave bursts. He concluded that best results were obtained by using the effective duration as a predictor.

The latter of these is an extension of Straka's study at 8.8 GHz and provides the primary input to a program recently developed by Smart and Shea (in preparation) which predicts the time behavior of the flare particle spectrum. (A third method of predicting the intensity of PCA events which is currently in use at AFGWC was developed by Kuck (ref 13) and Kuck et al (ref 14). It is based on the parent-flare soft X-ray emission.)

The main difference between this study and those summarized in table 1 is that the data sample considered here is much larger. First of all, more events have been observed since Castelli et al (ref 12) reported their results. Second, correlating with riometer absorption rather than satellite-measured particle flux allows one to include events from the nineteenth solar cycle. As an added bonus, many of these early absorption events are among the largest ever observed. The predictor used is that which, over the years, has emerged as the most reliable – event energy. The physical reason for expecting radio-event energy to be correlated with peak particle flux is that the radio energy should be proportional to the number of electrons accelerated which should, in turn, according to neutrality arguments, be approximately equal to the number of positive ions which are accelerated. Finally, the choice of the radio frequency for this study was dictated both by Straka's preliminary indication that low microwave frequencies are superior for predicting peak riometer absorption and also by the availability of the excellent 2.8-GHz (10.7-cm) observations by Covington at Ottawa throughout the nineteenth and twentieth solar cycles.

DATA CONSIDERATIONS

The selection criteria for the events were as follows:

(a) 30-MHz riometer absorption $\geqslant 0.5$ dB;

(b) Visible hemisphere parent flare; and

(c) Parent flare observed by Ottawa (nineteenth solar-cycle events only).

Criterion (a) was imposed because 0.5 dB is near the lower limit of riometer sensitivity. The prediction threshold beyond which AFGWC notifies customers of an impending polar-cap event is 1.0 dB of nighttime absorption and 2.0 dB of daytime absorption.

Criterion (b) is necessary because, for limb events, (1) radio (and optical) source regions are occulted by the disk by an unknown amount, and (2) particle propagation effects may play a dominant role.

Criterion (c) was adopted because of the availability and consistency of the Ottawa data.

By the mid 1960s, coverage of the sun at or near 2.8 GHz was virtually complete and all twentieth solar-cycle events which met criteria (a) and (b) were included in the sample. In all, 70 events satisfied the criteria. These events are listed in tables 2 and 3. For all events in table 2, the radio emission of the parent flare met or exceeded the 500-Sfu peak flux density* "bell-ringer" criterion of the Air Weather Services Space Environmental Support System (SESS) network of observatories at some frequency, f, $\geqslant$ 1415 MHz. The parent flares listed in table 3 did not produce (or would not have produced) a radio-event warning.

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13. AFWL Technical Note WLRTH, Prediction of Polar Cap Absorption Events, by GA Kuck, 1971
14. AFWL Technical Report 21-1, Prediction of Polar Cap Absorption Events, by GA Kuck, RR Davis, and GJ Krause, 1971

* 1 Sfu = 1 solar flux unit = 10^{-22} watt·m^{-2}·Hz^{-1}

TABLE 2. PARAMETERS OF ANALYZED EVENTS.

Date	H-α Peak Time	Optical Flare Class	Solar Coordinates	McMath Plage Region	2.8-GHz Event Energy (Sfu·min)	30-MHz Riometer Absorption (dB)	* Observatory	Notes
24 Jul 57	1828	3	S24,W27	4070	33 350	2	O	
31 Aug 57	1312	3	N25,W02	4124	71 175	4.9-5	O	
20 Oct 57	1642	3+	S26,W45	4189	51 000	5	O	1
22 Aug 58	1450	3	N18,W10	4708	42 600	>10-10.6	O	2
10 May 59	2140	3+	N18,E47	5148	174 667	>15-22	O	2,3
16 Jul 59	2132	3+	N16,W31	5265	173 333	>15-21.2	O	2,4
06 May 60	1440	3+	S08,E07	5653	17 550	8.7->15	O	2,5
12 Nov 60	1330	3+	N27,W04	5925	146 200	>14->22	O	2
11 Jul 61	1700	3	S07,E32	6171	41 400	1-1.5	O	2
20 Jul 61	1621	3	S06,W90	6171	21 000	5	O	6
10 Sep 61	2010	1	N08,W80	6212	18 300	2.9-5.5	O	2
16 Sep 63	1505	2	N12,E48	6964	19 358	0.8	O	
24 Mar 66	0237	2N	N20,W42	8207	1 260	1.8	N	7
07 Jul 66	0040	2B	N35,W48	8362	19 965	2.1	N	7
28 Aug 66	1529	3B	N22,E05	8461	16 165	2.4	O	8
02 Sep 66	0600	3B	N24,W56	8461	16 905	12.0	N	7,9
23 May 67	1947	3B	N28,E28	8818	174 675	11.0	O	10
28 May 67	0543	3B	N28,W32	8818	9 180	4	N	7
02 Nov 67	0856	2B	S18,W02	9047	1 000	0.9	Ne	11
09 Jun 68	0854	3B	S14,W09	9429	8 611	6.5	M	12
08 Jul 68	1715	3B	N13,E58	9503	22 320	1.1	SG	
26 Sep 68	0031	2B	N14,E34	9687	1 518	0.8	M	12
28 Sep 68	0753	2B	S18,E39	9692	11 881	1.2	M	13
29 Sep 68	1623	2B	N17,W51	9678	4 930	1.7	O	
31 Oct 68	0012	3B	S14,W37	9740	30 968	5.5	M	12
01 Nov 68	0903	2N	S16,W47	9740	67 000	5.9	Ne	11
02 Dec 68	2119	1N	N20,E89	9802	2 520	4.3	P	14
25 Feb 69	0913	2B	N13,W37	9946	14 736	2.1	SL	
26 Feb 69	0427	2B	N13,W46	9946	13 965	0.9	M	13
27 Feb 69	1413	2B	N13,W65	9946	6 840	1.1	O	15
12 Mar 69	1742	2B	N12,W80	9966	7 560	0.7	O	
21 Mar 69	0149	2B	N20,E17	9994	10 286	0.8	M	13
07 Jun 69	0955	1N	N11,E34	10134	340	1.4	SG	
24 Nov 69	0919	2B	N15,W31	10432	20 085	0.7	Ne	11
29 Mar 70	0046	2B	N13,W37	10641	21 259	1.8	L	

TABLE 2. (Continued).

Date	H-α Peak Time	Optical Flare Class	Solar Coordinates	McMath Plage Region	2.8-GHz Event Energy (Sfu·min)	30-MHz Riometer Absorption (dB)	* Observa-tory	Notes
15 Apr 70	0419	2B	N13,W86	10670	10 395	2.0	M	12,16
23 Jul 70	1843	1B	N09,E09	10845	4 805	4.7	O	17
05 Nov 70	0330	3B	S12,E36	11019	8 893	0.8	M	12,18
11 Dec 70	2241	1N	N16,W02	11073	14 110	0.5	M	13
24 Jan 71	2316	3B	N18,W49	11128	30 555	6.3	M	12
06 Apr 71	0944	1N	S19,W80	11221	5 813	2.2	M	12,19
05 Mar 72	0816	1B	S07,E43	11769	4 830	3.4	M	12,20
28 May 72	1332	2B	N09,E30	11895	24 295	2.2	O	
02 Aug 72	2058	2B	N14,E28	11976	379 200	8.5	O	21
04 Aug 72	0640	3B	N14,E08	11976	124 630	16.0	M	12,22
07 Aug 72	1534	3B	N14,W37	11976	70 980	14.0	O	23
30 Oct 72	0731	1B	S10,W03	12094	523	2.6	M	12,24
29 Apr 73	2104	2B	N14,W73	12322	68 640	1.2	O	25
03 Jul 74	0840	2B	S14,E08	13043	6 873	1.8	M	12,26
04 Jul 74	1357	2B	S16,W08	13043	34 695	4.6	O	27
10 Sep 74	2155	2B	N10,E61	13225	49 350	3.0	O	
19 Sep 74	2240	2N	N09,W62	13225	21 675	3.0	P	
05 Nov 74	1538	1N	S12,W78	13310	230	0.5	O	
21 Aug 75	1542	1B	N28,W76	13811	141	0.6	O	
30 Apr 76	2108	2B	S09,W47	14179	9 904	2.6	L	

*O = Ottawa; N = Nagoya; M = Manila; SG = Sagamore Hill; Ne = Nederhorst; P = Penticton; SL = Slough; L = La Posta

NOTES TO TABLE 2

(1) A riometer absorption value of 7.8 dB was also reported.

(2) The midpoint of the range of riometer absorption values was used in the correlations.

(3) A sudden commencement of a great geomagnetic storm (GMS) occurred on 11 May at 2330 UT, near the time of maximum riometer absorption.

(4) A sudden commencement on 17 July at 1638 UT which preceded a great GMS is associated with the observed particle flux maximum of this flare. Peak riometer absorption occurred on 17 July at ~10 hours UT.

(5) A sudden commencement of great GMS occurred on 08 May at 0421 UT, near the peak of the PCA event.

(6) The peak time listed is that of the 2.8-GHz emission.

(7) The radio observations for this event are at 2.0 GHz.

(8) A GSSC occurred on 29 Aug at 1315 UT, ~22 hours after the flare and ~12 hours before the PCA event maximum.

TABLE 2. (Continued).

(9) Following Švestka and Simon (ref 15), the PCA maximum is taken at 2330 UT.

(10) A GSSC occurred on 24 May at 1726 UT, ~22 hours after the flare and ~19 hours before the PCA event maximum. A second SC occurred on 25 May at ~12 hours UT, near the peak of the PCA event.

(11) The radio observations for this event are at 3.0 GHz.

(12) The 2.8-GHz event energy was measured from published Manila strip-chart records.

(13) The Manila strip-chart record was not available for this event.

(14) Geomagnetic storm modulation with sudden commencement on 05 Dec at 0633 UT is listed as a definite source of particles for a subsequent PCA event. The peak riometer absorption for the flare-associated event occurred on 05 Dec at 0942 UT.

(15) A major magnetic storm began at 03 hours UT and had its maximum at 18 hours UT, near the peak of the PCA event.

(16) A sudden commencement occurred at 1947 UT on 16 April, near the peak of the PCA event.

(17) The absorption "spike" of 4.7 dB is associated with a GSSC at 2350 UT on 24 July, ~24 hours after the prompt phase of the particle event. An earlier sudden commencement which occurred on 24 July at ~11 hours UT was probably associated with a 2B flare (N09,E32) with maximum at 0032 UT on 22 July.

(18) A sudden commencement occurred at 0046 UT on 07 Nov, about 6 hours before the peak of the low-energy particle event.

(19) The radio event was observed shortly before sunset at Manila.

(20) Castelli (GSDB, Appendix A) and Van Hollebeke et al list a -N event (S07,E40) with maximum at 1141 UT as an additional source of particles for this event. A sudden commencement was recorded at ~21 hours UT on 06 March, 1 hour before the PCA maximum was recorded at Thule and ~37 hours after the flash phase of the 1B flare.

(21) A sudden commencement associated with an earlier flare on 02 Aug (1B; N14,E35; 0410 UT) occurred at 0119 UT on 04 Aug. The sudden commencement associated with this flare occurred on 04 Aug at 0221 UT (ref 16). The 30-MHz absorption reached a peak of 8.5 dB at ~06 hours UT on 04 Aug. Following Castelli and Van Hollebeke et al, the 1B flare on 02 Aug is considered to be a contributing source of particles for the PCA event.

(22) The Thule 30-MHz riometer saturated at ~12 hours UT.

(23) Sudden commencements occurred on 08 Aug at 2354 UT and on 09 Aug at 0037 UT. The first SC is associated with this flare. Maximum riometer absorption was recorded at Thule at ~22 hours on 08 Aug.

(24) The flare association for this event is after Castelli. Van Hollebeke et al identify an earlier flare (2N; S10,E05) reported by Huancayo as the particle source. This flare began at 1544 UT on 29 Oct and lasted over 4.5 hours. Radio activity, during this time period, consisted of a gradual rise and fall event beginning at 1550 UT and ending at 2108 UT with superimposed complex events peaking at 1615 UT and 1753 UT. In all, the 2.8-GHz energy totaled nearly 8000 Sfu·min. Castelli lists this earlier flare as a possible contributing source of the particle event. The flare in the table was chosen as the principal particle source because it is a more likely candidate to have produced the shock responsible for the SSC on 31 Oct at 1654 UT, near the peak of the absorption event. The radio emission of this flare was moderately intense at the higher microwave frequencies (Sp = peak flux density = 940 Sfu at f = 8.8 GHz). Also Huancayo was the only observatory of three on patrol between 15 hours UT and 20 hours UT on 29 Oct which assigned an importance classification of 2N to the central disk activity. The other two stations reported only subflares.

(25) This flare was the source of energetic particles which produced a ground-level event but apparently it produced relatively few low-energy protons.

TABLE 2. (Continued).

(26) Following Castelli, possible contributing flares had maxima at 0716 UT (1N; S13,E17) on 02 July and 0840 UT (2B; S14,E08) on 03 July.

(27) Castelli lists a total of seven events occurring on 04 and 05 July which may have contributed to this particle event. Of these, the event in the table was the most energetic at centimetre wavelengths. Sudden commencements occurred on 05 July at 1930 UT and on 06 July at 0322 UT. It is believed that the first SC is associated with the previous flare in the table and the second with the flare under discussion. The PCA maximum was recorded on 05 July at ~20 hours UT. It is suggested that the magnetic field of the shock front responsible for the first sudden commencement inhibited the prompt low-energy particle response of this flare.

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15. Švestka, Z, and Simon, P, "Proton Flare Project," Solar Physics, v 10, p 3, 1969
16. Dryer, M, Eviatar, A, Frohlich, A, Jacobs, A, Joseph, JH, and Weber, EJ, "Interplanetary Shock Waves and Comet Brightness Fluctuations During June-August 1972," Journal of Geophysical Research, v 80, p 2001, 1975

TABLE 3. EVENTS FOR WHICH THE PARENT-FLARE PEAK RADIO EMISSION <500 Sfu (f ≥1415 MHz).

Date	H-α Peak Time	Optical Flare Class	Solar Coordinates	McMath Plage Region	2.8-GHz Event Energy (Sfu·min)	30-MHz Riometer Absorption (dB)	2.8-GHz Peak Flux Density (Sfu)	2.8-GHz Duration (min)	Observatory	Notes
26 Sep 57	1952	3	N22,E15	4159	2 040	2	67	60	O	
15 Jul 61	1512	2	S07,W20	6171	91	≤1.0	76	7	O	1
10 Nov 61	1444	1+	N19,W90	6264	1 748	1-2.2	124	38	O	
05 Feb 65	1810	2	N08,W25	7661	1 843	1.6	43	97	O	
13 Feb 67	1820	3B	N21,W11	8687	2432	0.5	50	127	O	2
16 Dec 67	0255	3N	N23,E66	9118	1 575	0.8	355	45	N	3
04 Oct 68	0020	2B	S17,W36	9692	9 050	1.6	108	168	M	4,5
24 Jan 69	0728	3B	N20,W08	9879	3 037	1.2	176	101	M	4,6
25 Sep 69	0753	3N	N13,W15	10326	1 712	0.7	35	107	Ne	7
07 Mar 70	0152	2B	S12,E10	10614	694	2.4	119	12	M	4,8
30 May 70	0319	2N	S08,W32	10760	2 441	1.0	16	300	T	9
19 Jan 72	1644	1B	S15,E12	11693	1 428	1.8	10	255	O	10,11
	0958	1N	S10,E11	11926	372		130	14	SG	
15 Jun 72	1313	1F	S14,W00	11922	16 815	2.2	57	590	O	12
07 Sep 73	1202	2B	S18,W46	12507	3 180	1.5	284	94	SG	11
29 Jul 73	1329	3B	N14,E45	12461	6 618	0.5	98	335	O	11

TABLE 3. (Continued).

NOTES TO TABLE 3

(1) The riometer absorption was superimposed on an earlier absorption event.

(2) Geomagnetic storm modulation, with sudden commencement at 2348 UT on 15 Feb, is listed as a definite contributing source of particles.

(3) The radio observations are at 2.0 GHz.

(4) The Manila strip-chart record was not available for this event.

(5) The peak time is that of the 2.8-GHz emission.

(6) Observations at Manila were terminated by sunset.

(7) Radio observations are at 3.0 GHz. The peak time is that of the 3.0-GHz emission.

(8) Van Hollebeke et al list a 1B flare (S14,E48) with maximum at 1128 UT as the source of particles for this event. However, the flare in the table is a more likely candidate to have produced the shock front responsible for the sudden commencement on 08 Mar at ~15 hours UT that was associated with the peak of the riometer absorption event. Neither event was very impressive at radio wavelengths.

(9) The radio observations are from Toyokawa at 2.0 GHz.

(10) A sudden commencement was observed on 21 Jan at 1151 UT, near the peak of the PCA event.

(11) The flare association for this event is after Castelli.

(12) Coordinated observations of these flares during the CINOF program (ref 17-20) suggest that both flares may have contributed to the particle event. In Figure 1, the sum of the event energies is used. Sudden commencements occurred at 0630 UT and 1311 UT on 17 June. The second SC has been associated with the flare at 0958 UT on 15 June. The Shepherd Bay riometer peaked at ~18 hours UT on 17 June.

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17. Dodson, HW, and Hedeman, RE, "A Small Subflare in the CINOF Program: June 1972, $14^d, 19^h, 36^m$ UT," AFCRL Technical Report 75-0437, 1975

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The 2.8-GHz energy listed in tables 2 and 3 is that of the main radio event; ie, it does not include the energy of the precursor and post burst increase which often accompany large bursts. The energies have been calculated from the burst durations and mean flux densities listed in Solar Geophysical Data (SGD), the Quarterly Bulletin of Solar Activity (QBSA), and the Geophysics and Space Data Bulletin (GSDB). As pointed out by Straka and Barron (ref 8), using the relationship

$$E = S_M \cdot T \tag{1}$$

where

E = Burst Energy (Sfu·min),

S_M = Mean Flux Density (Sfu),

T = Duration (min),

to determine event energy is not without its risks. The eyeball methods often used to obtain the mean flux densities of complex bursts can result in significant errors – as much as a factor of two. For 36 of the 70 events, the 2.8-GHz energy was calculated from the accurate Ottawa and Penticton burst parameters. In addition, profiles of large bursts are often published in data compilations, enabling us to measure directly the area under the curve for these events and further reduce probable error. The energies of 12 more events were determined in this manner. Following Wefer (ref 21), the energy is given in the convenient units of Sfu·min, rather than in the more conventional units of joules per square metre per hertz ($J \cdot m^{-2} \cdot Hz^{-1}$). As a final comment on the radio data, it should be noted that Ottawa and La Posta observe the sun at 2.8 GHz while the nominal frequency of observation at Sagamore Hill and Manila is 2695 MHz. In actual practice, of course, this slight difference in frequency is generally not significant and in this report all such observations are referred to as being at 2.8 GHz. For a few twentieth solar-cycle events, observations were not available at 2.8 GHz; for these cases, the parameters of the next closest reported frequency were used to calculate the energy. All such exceptions are noted.

For events occurring before 1970, the peak riometer absorption value and the identification of the parent flare were taken from reference 22. Only those catalog events with definite parent-flare associations were included in the sample. For PCA events occurring since 1969 for which there was some question about the assignment of a parent flare, the list of Van Hollebeke et al (ref 23) and appendix A of the GSDB were consulted. For these events the source of the parent-flare identification is indicated in the notes. Riometer absorption values for the post-1969 events were taken primarily from the GSDB and also from Cormier's report on events observed at Thule (ref 24).

Large, favorably located ($45°E \lesssim \varphi_{\odot} \lesssim 90°W$) flares often produce a delayed increase in riometer absorption associated with a geomagnetic storm sudden commencement. The sudden commencement is caused by the flare-produced shock front hitting the earth's magnetic field. Low-energy protons, trapped in the magnetic field of the shock, account for the enhanced absorption. Typical delay times between flare maximum and geomagnetic storm onset range from 24 to 48 hours for an event at 45°W and from 48 to 72 hours for a flare at 45°E. There is considerable scatter about these time ranges depending upon both the size of the flare and the condition of the preflare interplanetary medium. Thus, identifying the flare responsible for a delayed absorption increase is inherently more difficult than identifying the source of a prompt particle event. This is an important consideration since the delayed riometer absorption peak associated with the sudden commencement often exceeds the earlier prompt-particle induced enhancement. The times of sudden commencements which may have influenced or determined the time of the PCA maximum are given in the notes to tables 2 and 3. These times are taken from reference 22 for events occurring before 1970 and from the SGD Prompt Reports or reference 25 for later events. Unless it is otherwise noted or is obvious from the delay times that it cannot be so, it is to be assumed that the sudden commencement is associated with the flare in the table.

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ANALYSIS, RESULTS, DISCUSSION

As a first approach to the problem, peak riometer absorption (A) was plotted against 2.8-GHz event energy (E) for the 70 events listed in tables 2 and 3. A power-law relationship between the variables was obtained by the standard least-squares technique. The equation of the line in figure 1 is

$$\begin{aligned} A\ (\mathrm{dB}) &= 0.0940\ E(\mathrm{Sfu \cdot min})^{0.3498} \\ R &= 0.62 \end{aligned} \tag{2}$$

According to this prescription, a 2.8-GHz burst with $E \approx 6000$ Sfu·min will be associated with a principal riometer absorption event. However, inspection of a list of radio events compiled in SGD or elsewhere reveals many such events which do not have proton association. The 500 Sfu SESS "bell-ringer" criterion is designed to lower the PCA alert false-alarm rate by calling attention to only those flares which can, on the basis of statistics, be expected to produce protons. Figure 2 is a plot of A versus E for the 55 events in table 2. The best power-law fit to the data is given by

$$\begin{aligned} A\ (\mathrm{dB}) &= 0.0799\ E(\mathrm{Sfu \cdot min})^{0.3702} \\ R &= 0.61 \end{aligned} \tag{3}$$

This equation is not significantly different from equation (2). In order to achieve an acceptable false-alarm rate it is necessary to take the process a step further. In figure 2, 32 of the 34 (94 percent) principal absorption events are related to flares which had 2.8-GHz energy in excess of 3000 Sfu·min. If we restrict the sample to include only those events with parent flare 2.8-GHz energy $\geqslant 3000$ Sfu·min, we have figure 3. The equation of the solid line is given by

$$\begin{aligned} A\ (\mathrm{dB}) &= 0.0116\ E(\mathrm{Sfu \cdot min})^{0.5555} \\ R &= 0.59 \end{aligned} \tag{4}$$

This formula provides greater discrimination between those flares which are capable of causing a principal polar-cap event to occur and those which are not. It predicts that protons ejected from flares with $E \gtrsim 11\,000$ Sfu·min at 2.8 GHz will produce $\geqslant 2.0$ dB of 30-MHz riometer absorption. As a comparison, in appendix A of the GSDB, Castelli adopts a burst energy of $10^{-17}\ \mathrm{J \cdot m^{-2} \cdot Hz^{-1}}$, or 1667 Sfu·min at a given microwave frequency as one of the criteria which a flare should meet to be considered as a possible source of protons (at least 1 $\mathrm{proton \cdot cm^{-2} \cdot s^{-1} \cdot str^{-1}}$) for $E > 10$ MeV, or after Kuck et al (ref 14) $A \approx 0.6$ dB. In table 4, the 2.8-GHz energy threshold and the modified U-shaped spectral criterion (ref 3) are compared as yes or no predictors of principal PCA events for the 1968–1969 time frame. This table contains a complete list for these 2 years of relatively high solar activity of all 2.8-GHz bursts with $E \geqslant 10\,000$ Sfu·min, all radio events which satisfied the modified U criterion, and all $\geqslant 0.5$-dB riometer absorption events which had definite parent-flare associations.* For the period in question, it can be seen that the 2.8-GHz energy threshold compares reasonably well as a yes-no indicator.

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*The false-alarm radio events in the table were taken from observations of the Sagamore Hill and Manila observatories published in the GSDB. It is possible that a few such events occurred during gaps in the coverage of these two observatories and thus were missed. As in tables 2 and 3, whenever possible, the Ottawa burst parameters were used to calculate the energy or it was measured directly from the strip-chart records.

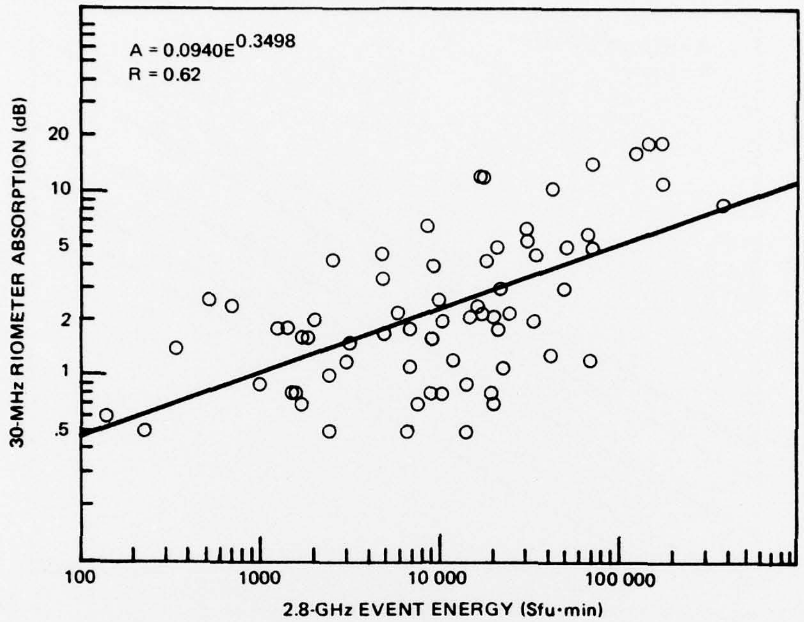

Figure 1. Riometer absorption versus event energy (all events).

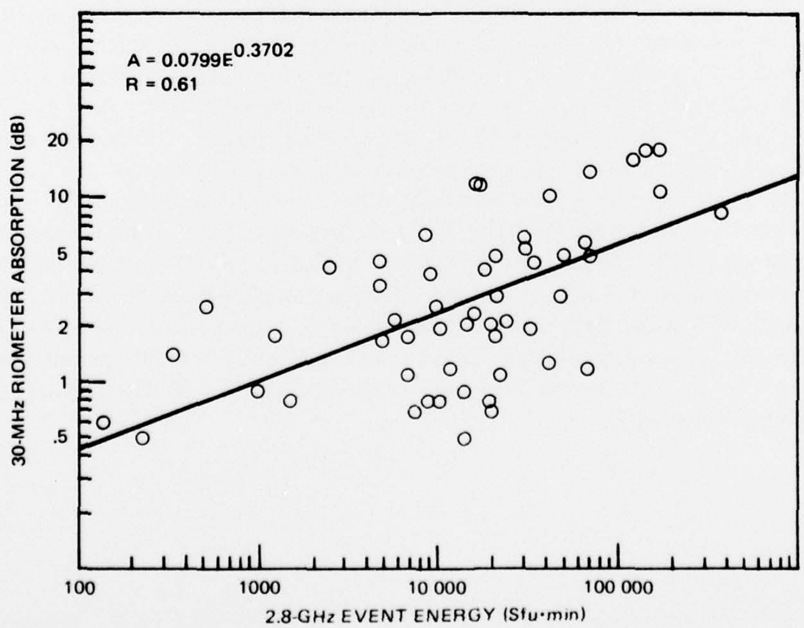

Figure 2. Riometer absorption versus event energy (table 2 events).

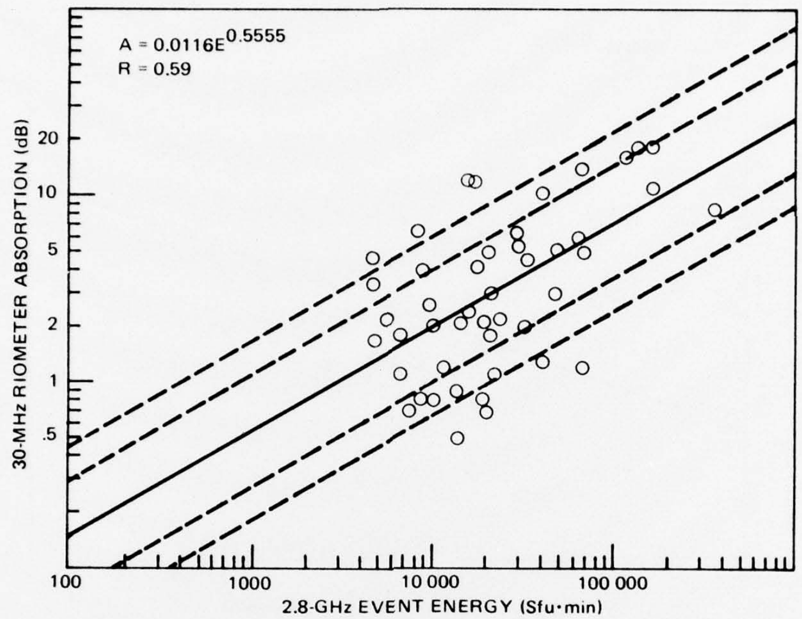

Figure 3. Riometer absorption versus event energy (table 2 events with E ⩾ 3000 Sfu · min).

The dashed lines in figure 3 indicate events which lie within factors of 2 and 3 of the least-squares line. Since the 10-MeV proton flux varies as the square of the riometer absorption (ref 26), these factors correspond to factors of 4 and 9 in the low-energy proton flux. Of the 32 principal PCA events in the figure, 22 (69 percent) would have been predicted within a factor of 2 and 28 (88 percent) would have been called within a factor of 3.

In conclusion, it has been shown that the use of equation (4), in conjunction with the modified U-shaped spectral (Castelli) criterion, can be expected to provide an accurate estimate of the size of an impending principal absorption event with a minimum of false alarms. A few comments on the limitations of this study are in order. First of all, no propagation correction has been built into this prediction tool. In figures 1–3, the eastern hemisphere events are scattered uniformly about the respective least-squares lines; however, there is a marked east-west asymmetry in the distribution of the 70 events on the solar disk (fig 4). Second, before any forecasting method can be accepted as valid, it must pass an operational test. The Polar Cap Absorption events of the twenty-first solar cycle will provide the necessary independent data sample.

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TABLE 4. PREDICTION METHOD APPLIED TO 1968-1969 EVENTS.

Date	H-α Peak Time	Optical Flare Class	Solar Longitude	McMath Plage Region	Riometer Absorption (dB)		Modified U-Shaped Spectral Criterion
					Predicted	Observed	
09 Jun 68	0854	3B	W09	9429	1.8	6.5	Yes
08 Jul 68	1715	3B	E58	9503	3.0	1.1	Yes
26 Sep 68	0031	2B	E34	9687	0.7**	0.8	Yes
28 Sep 68	0753	2B	E39	9692	2.1	1.2	No
29 Sep 68	1623	2B	W51	9678	1.3	1.7	Yes
04 Oct 68	0020	2B	W36	9692	1.8*	1.6	No
29 Oct 68	1518 1521	SN 1N	W82 W19	9735 9740	6.9	–	No
31 Oct 68	0012	3B	W37	9740	3.6	5.5	Yes
31 Oct 68	2303	2B	W49	9740	2.1	–	UNC
01 Nov 68	0903	2N	W47	9740	5.6	5.9	Yes
02 Dec 68	2119	1N	E89	9802	0.9**	4.3	Yes
24 Jan 69	0728	3B	W08	9879	1.0*	1.2	No
24 Feb 69	2315	2B	W31	9946	1.9	–	Yes
25 Feb 69	0913	2B	W37	9946	2.4	2.1	Yes
26 Feb 69	0427	2B	W46	9946	2.3	0.9	Yes
27 Feb 69	1413	2B	W65	9946	1.6	1.1	Yes
12 Mar 69	1742	2B	W80	9966	1.7	0.7	No
21 Mar 69	0149	2B	E17	9994	2.0	0.8	UNC
21 Mar 69	1334	2B	E09	9994	2.0	–	Yes
05 Jun 69	1010	2B	E64	10134	2.2	–	Yes
07 Jun 69	0955	1N	E34	10134	0.3**	1.4	No
25 Sep 69	0753	3N	W15	10326	0.7***	0.7	No
18 Nov 69	1654	2B	E40	10432	1.9	–	Yes
24 Nov 69	0919	2B	W31	10432	2.8	0.7	Yes

*Sp < 500 Sfu at f $\geq$ 1415 MHz
**E < 3000 Sfu · min at f = 2.8 GHz

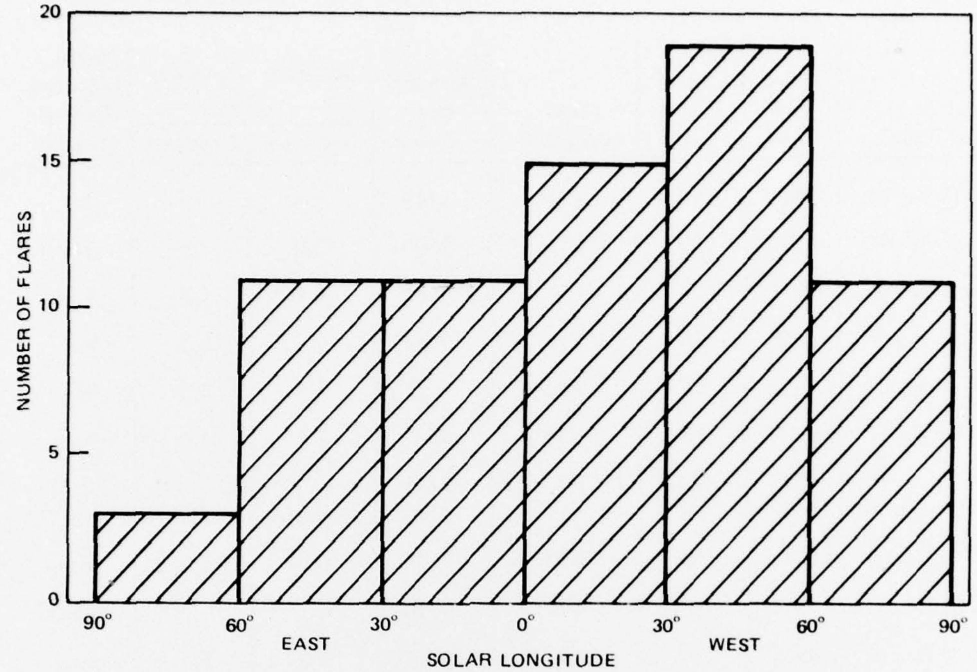

Figure 4. Longitudinal distribution of parent flares.

APPENDIX A: PARTICLE PROPAGATION CORRECTION

The proton prediction program developed by Smart and Shea for AFGWC contains a correction for the effect of the interplanetary magnetic field on particle propagation. Thus equation (4) must be modified if it is to be used as an input to their program; otherwise the predictions made will generally be too low.

A given proton flare will produce a maximum particle flux (measured at earth) when it is located at the solar footpoint of the Archimedes spiral which intersects the earth, and less when located elsewhere. According to Smart and Shea's prescription, the reduction in flux with distance of the flare from this footpoint goes as $e^{3\theta}$, where θ is the angle in radians between the heliographic longitude of the flare region and the longitude of the footpoint, both taken at the time of peak riometer absorption. The solar longitude of the footpoint of the Archimedes spiral field line which connects to the earth is given by

$$\text{Solar longitude of footpoint} = \frac{404.1}{V_s}\text{(radians)} \tag{A1}$$

where V_s is the solar wind speed in $km \cdot s^{-1}$. The National Space Science Data Center has compiled a comprehensive list of the solar wind measurements available for the period from 1964 to 1973. For events occurring before 1964 (or since during data gaps), a nominal V_s of $404.1\ km \cdot s^{-1}$ may be used, placing the footpoint at 1 radian or $\approx 57°$W. Smart and Shea's program takes into account other, higher order corrections, such as the effect of flare latitude, but the longitude effect is clearly dominant.

The procedure for incorporating the propagation correction into the basic result of this paper (or any other forecast scheme) so that it can be utilized in AFGWC's proton prediction program is as follows:

A. For each event in the data base:

1. Convert riometer absorption (A) into >5.2-MeV proton flux (J) using

$$J\,(\text{protons} \cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}) = \frac{A\,(dB)^2}{\pi(0.115)^2} \tag{A2}$$

after Stroscio and Sellers (ref 27). (The >5.2-MeV peak proton flux is used in these correlations because of its relative independence of the slope of the proton energy spectrum (ref 27.)

2. Determine θ at the time of peak riometer absorption, taking solar rotation into account.

3. Multiply the >5.2-MeV flux measured at the earth by $e^{3\theta}$ to obtain the flux at 1 au out on the Archimedes spiral which connects to the flare region.

B. Determine the relationship between the 2.8-GHz event energy (E) (or any other parameter) and the particle flux from (A) by the least-squares method.

The result of (B) for the 47 events considered in this paper is given in figure A1 and equation (A3).

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27. AFCRL Technical Report 75-0469, The Calculation of Riometer Absorption and an Approximate Connection Between Riometer Absorption and Solar Proton Fluxes During Night-time PCA Events, by MA Stroscio and B Sellers, 1975

$$J = 0.00129E^{1.4470}$$

$$R = 0.54 \qquad \text{(A3)}$$

The improvement in the correlation which one would hope to see, as affirmation of the validity of the propagation correction, is not apparent. It should be noted that Newell (ref 11) found a similar lack of improvement when he applied the propagation correction of Kuck et al (ref 14) to his list of events. Smart and Shea kindly provided a test run of their program for the 47 events using equation (A3) as the initial input. The predictions and observations are compared in figure A2. Twenty-nine events, or 62 percent, lie within a factor of 2 of the optimum line. Those events falling outside the acceptable range tend to be overpredicted. It is perhaps significant that only one of the 17 events with eastern hemisphere parent flares, ie, those events to which the largest correction factors are applied, is overpredicted by this method.

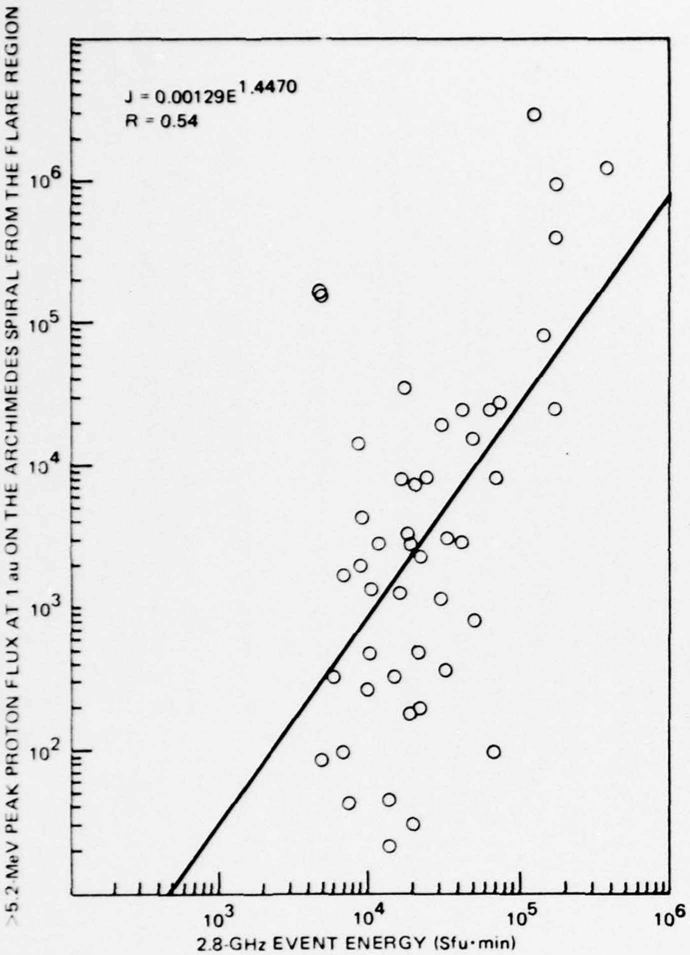

Figure A1. >5.2-MeV peak proton flux at 1 au on the Archimedes Spiral with footpoint in the parent-flare region versus event energy.

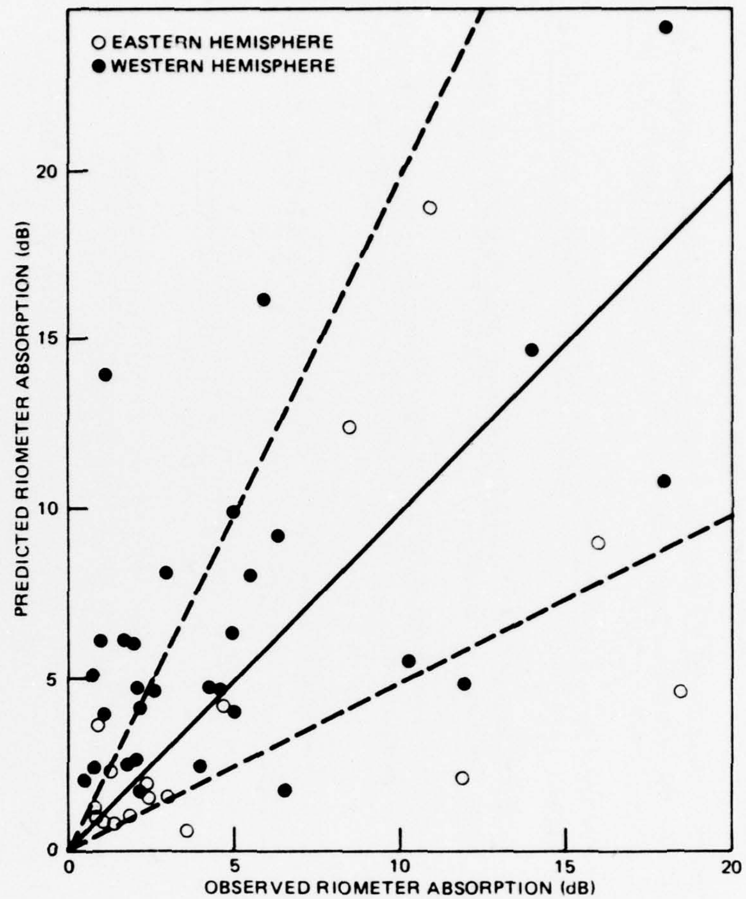

Figure A2. Results of the Smart and Shea prediction program using equation (A3) as the initial input.

APPENDIX B: REFERENCES

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